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METEOROLOGICAL FACTORS AFFECTING MIXED-LAYER DEPTH FLUCTUATION

RALPH A. ZETTEL

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by

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ABSTRACT

The general problem of modification of the ocean's thermal structure by meteorological influences is discussed. Meteorological factors associated with mixed-layer depth fluctuation at three ocean stations in the open Pacific Ocean are evaluated and discussed. Sea-surface temperature correlation with mixed-layer depth at ocean station PAPA to support the meteorological influence is also evaluated and discussed.

The author wishes to express his appreciation for the advice and assistance given by Professor G. H. Jung of the U. S. Naval Postgraduate School in this investigation, and also his thanks to the Pacific Oceanographic Group for making the oceanographic data available.

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TABLE OF SYMBOLS AND ABBREVIATIONS

ALFA	ocean station at 49N - 148W
ave	average
B	wind force in Beaufort Scale
C	centigrade
chg	change
CF	cold front
da	day
F	fahrenheit
ft	feet
GCT	Greenwich civil time
m	meter(s)
max	maximum
mb	millibar(s)
MLD	mixed-layer depth
ΔMLD	MLD change (as indicated)
$\overline{MLD}_{02}$	monthly mean MLD at 0200 GCT
$\overline{MLD}_{17}$	monthly mean MLD at 1700 GCT
$\Delta\overline{MLD}_{02-17}$	monthly mean diurnal MLD change, 0200 to 1700 GCT
$\overline{MLD}_{02,17}$	average of monthly mean MLD at 0200 and 1700 GCT
MLD_{24}	daily mean MLD (one or two observations, as available)
$\overline{MLD}_{24}$	monthly mean MLD from daily average (one or two observations, as available)
NOVEMBER	ocean station at 30N - 140W
Occ	occlusion
PAPA	ocean station at 50N - 145W
pr	prior

T	Trough
T_s	sea-surface temperature
ΔT	temperature change (as indicated)
$\bar{T}_{02}$	monthly mean sea-surface temperature at 0200 GCT
$\bar{T}_{17}$	monthly mean sea-surface temperature at 1700 GCT
$\Delta\bar{T}_{02-17}$	Monthly mean diurnal sea-surface temperature change, 0200 to 1700 GCT
$\bar{T}_{02,17}$	average of monthly mean sea-surface temperature at 0200 and 1700 GCT
T_{24}	daily mean MLD (one or two observations as available)
$\bar{T}_{24}$	monthly mean sea-surface temperature from daily average (one or two observations as available)
T_a-T_s	Air minus sea-surface temperature difference
WF	warm front
/	per

1. Introduction

One of the most significant factors determining commercial and military sonar effectiveness in any ocean area is the vertical temperature structure of the sea. Varying processes modify the thermal structure to produce an essentially homogeneous ocean layer on the sea surface, varying in thickness in time and space. Therefore, the prediction of the behavior of this homogeneous layer (mixed layer) and its thickness (mixed-layer depth, abbreviated MLD) has practical value.

Many authors have described how various physical processes modify the thermal structure to produce the MLD. In nature these processes either may act independently or may be dependent upon one another, making difficult isolation of distinct relationships and classification.

MLD fluctuations may be classified broadly according to: 1) general processes capable of causing fluctuations, or 2) predominant period of fluctuation. Interaction relationships across the air-sea interface suggest that MLD fluctuation is associated primarily with meteorological variables. Study of the meteorological factors associated with the general physical processes, and resulting relations with MLD variation, clarify the causes of MLD fluctuation.

The purpose of this paper is to attempt to correlate meteorological factors with MLD fluctuation and to determine which variables appear to contribute significantly. A particular parameter, such as sea-surface temperature, will be isolated for correlation with MLD to substantiate the meteorological influence on the MLD fluctuation.

The study also will investigate differences in such influences for the various periods of MLD fluctuation.

I. Background

There is general acceptance that the surface mixed layer exists 90% of the time on the sea surface [12]. In a general sense, the mixed layer varies with latitude. The surface layer is absent in high latitudes, a minimum in the equatorial region, and more pronounced in the mid-latitude area. This meridional variation of the mixed layer can be related broadly to the typical meridional temperature profile. In more detail, however, the MLD varies in time and space in response to variations in the physical processes.

Gilcrest [3] summarized the application of the Rossby and Montgomery [15] steady-state theory for the open ocean MLD applied by Lumby [10] to world-wide ocean areas below 60 degrees latitude. The quarterly charts developed by Lumby, using only wind statistics and an average stability parameter, are in substantial agreement with a summary [11] based upon hydrographic and bathythermograph data.

The time and space variation of the ocean thermal structure, hence MLD, has been depicted by Leipper [9] among others. However, the paucity of continuous data over ocean areas has made precise evaluation of MLD fluctuation difficult. Detailed studies of the temperature distribution (from which MLD may be inferred) have been accomplished by various investigators for particular areas based upon accumulated bathythermograph data available. Robinson [14] presented such material for the Northeast Pacific Ocean area which established general climatological features from which further study may proceed.

The general or key processes capable of causing MLD fluctuation are well known [12] and fall into the catagories of 1) heating, 2)

cooling, 3) mixing, and 4) advection. Other similar classifications have been used by various recent authors [2, 7, 8, 16] . One summary of the key atmospheric parameters (which will be defined as meteorological factors later) associated with these key processes has been presented by Jung [6] .

The predominant periods of MLD fluctuation have been described by Schule in five primary categories [16] . These categories are 1) seasonal; 2) lunar (monthly, bimonthly); 3) semi-diurnal and diurnal, tidal; 4) short period; and 5) random variations due to mixing.

?. The mechanism of meteorological influence

A meteorological motivating influence on MLD fluctuation will be defined as one operating through meteorological variables. That meteorological variables are physically capable of modifying the MLD has been indicated previously. Therefore, if it can be shown that correlation exists between meteorological factors and MLD fluctuations, those fluctuations will be classified as meteorologically motivated.

The mean annual march of the thermocline is the most basic variation in the MLD; this annual fluctuation can be related to annual climatic variations overlying the ocean region. Closer inspection reveals that the aggregate of the monthly mean depths of the thermocline usually tabulated actually are a representation of the annual march of the thickness of the surface mixed layer, or MLD. The smooth annual course of the MLD is made up of distinct shorter fluctuations occurring with pronounced regularity which are damped out by the averaging process. Observation reveals that the periods of MLD fluctuation range from annual (generally the largest in amplitude and the most regular) to short term variations of a few minutes or hours. Other periods within the MLD variation include long term, ranging from one to four weeks; diurnal, which are of 24 hour period; and seasonal.

Heat exchange processes provide basis for annual, seasonal, long term and diurnal heat exchange components. Relatively little is known about the short period variations currently ascribed to internal waves. Land and water surfaces are heated when exposed to radiation or warmer air; and they lose heat when insolation ceases, evaporation occurs, or cooler air overlies the surface.

Therefore, the sea-surface temperature could be considered as representing the integrated effects of the heat exchange parameters.

Change in air temperature normally preceeds sea-surface temperature change. Wind (mechanical mixing), is the principal cause of the sea-surface temperature variations when convective mixing is minimized [7] .

On land, where a relatively thin layer is warmed, the mean and diurnal air temperature variation follow closely the annual and daily variations of radiation. In the sea, summer radiation warms a thick water layer to a moderate temperature. Therefore, at sea, a time lag between maximum values of air and sea temperature is introduced. The sea-surface temperature varies less than one degree Centigrade diurnally, being usually lowest at 0600 and highest at 1500 local hours. The diurnal variation of both air and sea temperature is greatest on calm, clear days in summer, with generally smaller values at other times of the year. At the sea surface, it is known that short-term temperature variation occurs of the same range as diurnal fluctuations.

This study will first attempt to correlate meteorological factors with the long-term MLD fluctuations superimposed on the mean annual march of the MLD. Those variables which appear to contribute significantly will be isolated. A later section will seek correlation of sea-surface temperature with MLD for annual, seasonal and diurnal periods. The existence of correlation between sea-surface temperature and MLD would substantiate the supposed meteorological influence on annual, seasonal, long-term and diurnal MLD fluctuations.

4. Long-term mixed-layer depth fluctuation

Various meteorological variables were qualitatively related to the occurrence of a MLD minimum which is superimposed on the mean annual MLD fluctuation. Concurrent data [9, 18] of bathythermograph and meteorological variables were tabulated into time series and tested with more complete data [13, 17, 19] in the same general geographical area. The variables were tabulated by magnitude, range and time interval relative to the MLD minimum or 'peak'; and significant variables were isolated. Thereafter, any indication of sea-surface temperature correlation with MLD was noted which might merit additional study.

In order to minimize the influence of convective mixing and of tidal forces, data for the months of maximum sea-surface heating in the open Pacific Ocean were used.

Sea-surface temperature and MLD bathythermograph data were abstracted from Leipper [9] for May through September, 1949 for the preliminary investigation. Meteorological data were obtained from the U. S. Weather Bureau, Daily Series Synoptic Weather Maps [18] for the same period. Latitudinal comparison was made using two separated geographical locations, ocean stations ALFA (49N - 148W) and NOVEMBER (30N - 140W), where simultaneous bathythermograph and meteorological data were available.

These bathythermograph data represented five-day averages; hence, short period and diurnal fluctuation of sea-surface temperature and MLD were damped out. Moving-average smoothing on time-series data is known to reduce the magnitude of oscillation and may possibly induce phase shifts [4, 5] . The first highest apex

(called 'peaks') of each major MLD minimum was used for the preliminary investigation. It was assumed that the actual maximum MLD decrease of the daily values would be retarded by the smoothing process. Therefore, any association of meteorological variables with each major MLD minimum may possibly be more clearly identified using the first MLD 'peak'.

The independent test utilized more complete simultaneous bathythermograph and meteorological data provided by the Pacific Oceanographic Group [13] at ocean station PAPA (50N - 145W) for the year 1958. For this phase of the study, the author defined the MLD as the depth of the most prominent peak (or break) in the temperature-depth curve on the bathythermogram where (the shallowest) the temperature gradient is greater than 0.1C per ten meters. This definition eliminated from consideration the minor transitory negative gradients until a new isothermal layer was established. It also permits a zero MLD when the specified temperature gradient is exceeded at the ocean surface. Since more complete data were available for the test evaluation, each clearly defined running average MLD minimum ('peak') was used. In addition, the preliminary data used an MLD defined as:

> the depth of a $\pm$ 0.3F change from the temperature of the sea surface [9].

It then became necessary to determine whether moving-averaged curves constructed from daily values using either MLD definition would be of same form and MLD 'peaks' would occur on the same day. The curves acted similarly in relation to the daily values for both definitions, compared reasonably well in form, and produced no shift of the MLD

'peak' for June 1958 (table I). It was then assumed that no appreciable difference would occur for the remainder of the heating season for the test data, and results of ocean stations ALFA, NOVEMBER and PAPA could be compared. The daily sea-surface temperature and MLD used by the author for construction of the average curves will be explained in a later section.

The significant meteorological variables associated with the major MLD 'peaks' selected in the preliminary investigation for ocean station ALFA and NOVEMBER are shown by tables 1 and 2 respectively. The respective summaries of the tabular results are contained in tables 3 and 4.

The occurence of the same significant variables with the selected MLD 'peaks' of the test data for ocean station PAPA are shown by table 5. The summary of these results is contained in table 6.

The evaluation of the qualitative relations for ocean station ALFA and NOVEMBER (tables 3 and 4) was encouraging. The general features of the meteorological pattern noted for ocean station ALFA were in evidence at ocean station NOVEMBER. Wind force, total cloud cover, air-sea surface temperature difference and sea-state were the meteorological variables isolated which appeared to contribute most significantly to MLD long-term fluctuation. The significance of these meteorological variables could be explained by the physical processes introduced previously.

Some gross latitudinal differences were observed between the important variables at ocean stations ALFA and NOVEMBER. Absence

of clearly-defined surface cyclonic or frontal systems at ocean station NOVEMBER indicated that these phenomena were neither necessary nor sufficient for producing MLD 'peaks', but may accentuate the contributions of other variables. For example, the upper-atmospheric processes associated with a 500 mb depression could in turn influence lower atmospheric variables such as surface pressure and cloud cover. A decrease of wind force from high to low value in each case clearly indicated that a decrease in wind (mechanical) mixing was a primary requisite for a major decrease of MLD. Therefore, the degree to which the other factors become significant appeared to be a function of wind speed; this is emphasized since the latitudinal variation of each separate meteorological variable can be explained by the climatological difference between the two geographical locations. The form of the sea-surface temperature curves suggests that this variable may be used as an 'indicator' of MLD fluctuation. This will be discussed in the next section.

It was recognized that extreme caution should be exercised before drawing conclusions from investigations based on interdiurnal variability [1] . The curves described by the bathythermograph and meteorological data represent differences of the various elements at a fixed hour. The principal disadvantage is that the data would not represent mean daily values and significant changes of the variables between observations would not be detected. Test evaluation with independent and more complete bathythermograph and meteorological data was therefore necessary. The independent test would then verify the data representativeness (and the original postulates based upon such data).

The qualitative relation of significant meteorological variables for ocean station PAPA corresponded well with similar relations established for ocean station ALFA (tables 6 and 3). The contribution by total cloud cover to net effective radiation available to heat the sea surface was more clearly demonstrated. The actual maximum MLD decrease appeared to follow a critical reduction of cloud cover from preceeding conditions by one day; the amount of decrease depended on other meteorological variables (especially wind speed). The remainder of the data representativeness appear sufficiently reliable to support the original postulates; however, the value of complete data for this type of investigation was clearly demonstrated.

In summary, it was concluded that the long-term MLD fluctuation superimposed on the mean annual MLD can be associated with meteorological variables in the open Pacific Ocean for the period investigated.

This study is limited by the qualitative nature of the established relations and the subjective selection of data by the author. However, the associations appear significant enough to merit additional study.

5. Sea-surface temperature variation

In the previous section it was shown that the test data support the original premise that the sea-surface temperature appears to respond in general to the meteorological variables and represent their integrated effects. This relation indicated need for additional study to substantiate the meteorological influence on MLD fluctuation.

Sea-surface temperature and MLD from bathythermograms were then tabulated for the year 1958 at ocean station PAPA and organized into graphs and scatter diagrams.

In section 4, five-day running-mean data at a fixed hour for ocean station ALFA and NOVEMBER were compared with more complete data at ocean station PAPA. Hence, before discussion of the graphical results, it is in order to ask-

> can selection of values from a complete data series (such as PAPA) influence the shape of running mean curves derived from these data samples?

The soundings at 0200 and 1700 GCT are assumed representative of maximum diurnal effects, neglecting random fluctuations. An average of 0200 and 1700 could then represent a mean daily value of the parameters. In practice, observations from successive soundings may not be available. If an observation were missed for the day, then the remaining single observation was used rather than omitting the entire day. Table 7 is a comparison of various averaging techniques for June 1958. 'Individual' data defines averages for all observations known for the month at the specified times. Only those days when both observations were available were used for 'paired' averages. It can be seen that $\overline{T}_{24}$ and $\overline{MLD}_{24}$ of both individual

and paired data are within reasonable limits of $\overline{T}_{02,17}$ and $\overline{MLD}_{02,17}$. Evaluation reveals that these values approach equality as the density of 0200 and 1700 GCT observations approach a maximum. It was then assumed that the specified selection of daily values by the author for ocean station PAPA would be equally representative for construction of the sea-surface temperature and MLD average curves.

Figure 2 is a graph of monthly mean sea-surface temperature and MLD for the year 1958. Examination reveals the asymmetrical shape of the annual curve for both variables. It was postulated earlier that boundary exchange of energy determines the total amount of heat present. The sea-surface temperature lag behind the MLD could be explained by the particular thermal properties of water under the influence of radiational heating and mixing. It seems reasonable that since the variables are directly related, each should describe an asymmetrical shape. In general, the curves are similar to the familiar mean annual air and land surface temperature curves.

Figure 3 is a graph of mean diurnal sea-surface temperature and MLD for the maximum heating period of 1958, May through September. Comparison of these curves with the monthly mean MLD reveals a close correspondence. The magnitude of the sea-surface temperature variation appears to decrease as MLD increases. The variation increases with increasing stability of the surface layers. The variation of MLD varies in the opposite sense. Since convective mixing (as opposed to wind mixing) is minimal during the maximum heating season, the redistribution of heat in the mixed layer is primarily due to wind (mechanical) mixing.

The scatter diagrams of diurnal sea-surface temperature and MLD

variation by months for May through September, 1958, are shown in figures 4 through 8 respectively. These demonstrate increasing correlation during the course of the heating season, a maximum being reached for June and July and becoming progressively less distinct during August and September. The June and July data clearly represent the summer seasonal regime when net insolation markedly exceeds heat losses. The months of May and August could be considered transitional periods; and September, a period when heat losses across the air-sea interface exceed net insolation.

In general, the pattern of the preceding curves can therefore be considered a measure of the particular mixing processes invloved. In all four months, periods of high wind mix the surface layer to a greater depth, but only under conditions when net insolation markedly exceeds heat losses is there a tendency for the MLD to approach the surface under low wind conditions. The change of the May and August relationship from that of June and July appears to reflect the increasing influence of convective mixing then. In November (figure 9), when convective mixing is known to exert strong influence, the summer seasonal relationship falls apart and the scatter diagram points show a random distribution.

Variation of the observed results from mean climatological conditions at ocean station PAPA could possibly be explained by an abnormal heating season for 1958. Inspection of the sea-surface temperature curve in figure 10 shows an approximate displacement of the apex one month prior to the mean curve for several years. Therefore, convective mixing may have become an important factor earlier in 1958 than in most years.

6. Summary of meteorological factors

It has been demonstrated that meteorological factors may be associated with MLD fluctuation in some locations. Wind force, total cloud cover, air-sea surface temperature difference and sea-state were the meteorological variables isolated which appeared to contribute most significantly to MLD long-term fluctuation. The relation between sea-surface temperature and MLD variations of annual, seasonal and diurnal time-scales was also shown. This, together with the known relation of air to sea-surface temperature, more clearly establishes the meteorological influence on MLD.

Previous works have established that exchange of heat across the air-sea interface largely determines the total amount of heat present in the ocean surface layer. The sea-surface temperature therefore can be considered an 'indicator', representing the integrated effects of the meteorological variables on the ocean mixed layer.

It seems reasonable then, to consider that the mean annual fluctuation of MLD represents the net heat change of the layer acted upon by the redistributing processes, with wind (mechanical) and convective mixing as primary redistributing factors. Since the amount of heat exchange across the air-sea interface, as well as the wind field, varies both in time and space, then the associated MLD should vary seasonally, from year to year, and geographically.

It follows that the mean annual march of the MLD is 'meteorologically influenced'. Similarly, most of the distinct fluctuations appearing on the annual MLD curve also can be classified as 'meteorologically influenced'. Those MLD fluctuations of distinct tidal period

may then be classified further and termed 'astronomically influenced'.

The meteorological influence was demonstrated most clearly at ocean station PAPA, and it could be expected as well at adjacent deep ocean stations.

However, relative importance of the individual meteorological variables, as well as the total meteorological influence on MLD fluctuation, can be expected to change with location in the deep ocean, and when going from the deep ocean to coastal areas.

7. Conclusions

The long-term MLD fluctuations investigated in the open North Pacific Ocean at three ocean stations may be qualitatively related to variation in meteorological factors.

Wind force, cloud cover, air-sea surface temperature difference and sea-state are the meteorological variables which appear to contribute significantly to MLD long-term fluctuation. Wind (mechanical) mixing and cloud cover appeared to be the most important of these variables.

The MLD fluctuations may be broadly classified as 1) meteorological -- annual and synoptic periods; 2) astronomical -- tidal internal wave period; and 3) others, including internal waves of random period. The meteorological influence was the most significant of these at ocean station PAPA during the period investigated.

8. Recommendations for further study

Wind force, cloud cover, and the difference between air and sea-surface temperature relationships associated with MLD fluctuation appear to warrant additional study to evaluate their integrated effects more quantitatively.

Sea-surface temperature shows promise as a good 'indicator' of MLD fluctuation. Additional investigation of the annual, seasonal, and daily sea-surface temperature versus MLD may further define this relationship.

Extension of the research to the remaining portion of the year and to other years of data for the Pacific Ocean will further establish the thermal structure climatology of the area.

Collection of simultaneous bathythermograph and meteorological data should be expanded to other ocean areas on a continuing basis to provide an areal coverage of basic data for this type of analysis.

Ocean Station ALFA

Date	Synoptic 500 mb	Data surface	Cloudiness (8ths)	Wind Force (Beaufort)	Sea (coded)	$T_a - T_s$ (mean trend & max -C)	T_s (trend & ave max)	Pressure (mb)	Δ MLD (m)
9 May	T 3 da pr	Low 4 da pr	-8/1 da same da (0)	-4/5 da 2 da pr (2)	-5/5 da 3 da pr (2)	+/8 da 1 da pr (+1)	+ + same da	-14/3 da 1 da pr	-50.2/5 da (22.8)
21 May	T 3 da pr	Low 4 da pr	-8/1 da 3 da pr (0)	-5/3 da 2 da pr (1)	-4/4 da 1 da pr (1)	+/4 da 3 da pr (+2) 4 da pr	+ + 1 da later	-7/3 da 4 da pr	-18.3/4 da (10.7)
6 Jun	T 3 da pr	Occ 4 da pr	-6/2 da same da (2)	-4/3 da same da (3)	-4/3 da same da (2)	+/7 da 3 da pr (+2) 4 da pr	+ + same da	-26/5 da 4 da pr	-17.7/4 da (12.8)
10 Jul	T 5 da pr	Occ 6 da pr	0 chg (8)	-4/2 da 2 da pr (3)	-5/2 da 2 da pr (2)	+/4 da same da (+1)	+ + 2 da later	-28/4 da 4 da pr	-8.3/4 da (14.6)
17 Jul	T 4 da pr	T 4 da pr	-1/1 da 5 da pr (7)	-3/2 da 2 da pr (2)	-4/2 da 2 da pr (2)	+/2 da 2 da pr (0)	+ + 2 da later	-7/2 da 6 da pr	-7.6/4 da (15.3)
25 Jul	T 3 da pr	CF 3 da pr WF 2 da pr	0 chg (8)	-3/1 da 2 da pr (3)	-3/1 da 2 da pr (2)	+/5 da same da (+1)1 da pr	+ + 4 da later	-4/2 da 3 da pr	-3.1/2 da (22.3)
5 Aug	T 6 da pr T same da	Low 6 da pr Low 1 da pr	0 chg (8)	-3/1 da 2 da pr (4)	-2/1 da 2 da pr (3)	+/6 da 2 dalater (+1)1 da later	+ + same da	-23/6 da 3 da pr	-5.5/5 da (25.0)

Table 1. Meteorological Variables Associated with Major MLD 'peaks', May through September, 1949 (2 pages)

Ocean Station ALFA

Date	Synoptic Data 500 mb	Synoptic Data surface	Cloudiness (8ths)	Wind Force (Beaufort)	Sea (coded)	T_a-T_s (mean trend & max -C)	T_s (trend & ave max)	Pressure (mb)	Δ MLD (m)
21 Aug	T 4 da pr	Low 4 da pr	0 chg (8)	-4/1 da 3 da pr (1)	-4/5 da 1 da pr (1)	+/8 da same da (+3)	+ 2 da later	-16/4 da 5 da pr	-19.8/5 da (13.7)
6 Sept	T 5 da pr	Occ 5 da pr	0 chg (8)	-5/3 da same da (1)	-5/4 da 1 da later (3)	+/3 da 2 da pr (+4) 3 da pr	+ 2 da later	-6/1 da 1 da pr	-8.6/4 da (17.4)
23 Sept	T same da	Low 1 da pr	-6/2 da same day (2)	-2/3 da 2 da pr (4)	-3/5 da 2 da pr (6)	+/9 da 2 da later (-2)1 da later	+ same da	-19/4 da 2 da pr	-7.6/3 da (24.4)

Table 1. Meteorological Variables Associated with Major MLD 'peaks', May through September, 1949 (cont'd)

Ocean Station NOVEMBER

Date	Synoptic Data 500 mb	Synoptic Data surface	Cloudiness (8ths)	Wind Force (Beaufort)	Sea (coded)	T_a-T_s (mean trend & max -C)	T_s (trend & ave max)	Pressure (mb)	ΔMLD (m)
3 May	T 1 da pr		-4/1 da same da (4)	(2)2 da pr	0/2 da same da (2)	+/2da same da (-1)1 da pr	+ + same da		-11.6/2 da (34.2)
12 May	Low 1 da pr	T 3 da pr	-5/3 da 1 da pr (2)	-2/1 da 2 da pr (2)	0/4 da 2 da pr (2)	+/3 da 1 da pr (+2) 2 da pr	+ same da	-8/6 da 2 da pr	-20.4/2 da (30.5)
9 Jun	Low 2 da pr		-3/2 da same da (2)	-3/2 da 1 da pr (1)	-3/3 da 1 da pr (1)	+/9 da 2 da later (-1)1 da later	+ + 2 da later	-8/4 da 1 da pr	-39.0/5 da (3.7)
24 Jun	Low 1 da pr		-6/2 da 1 da pr (2)	0 chg/5 da 1 da pr (4)	-6/9 da 3 da later (1)	+/4 da 1 da later (-2)same da	+ 1 da later	-6/3 da 1 da pr	-19.2/3 da (22.8)
1 Jul	T 1 da pr		-2/1 da same da (6)	-1/1 da 1 da pr (3)	0/3 da same da (2)	+/3 da 1 da pr (0)	+ 2 da later	-1/3 da 1 da pr	-17/2 da (21.4)
13 Jul	Low 2 da later		-1/1 da same da (7)	-4/2 da same da (4)	-2/1 da same da (4)	+/8 da same da (0)	+ + 1 da later	-8/3 da 2 da later	-9.2/3 da (33.6)
29 Jul	T 5 da pr		-6/6 da 2 da pr (2)	-3/3 da 1 da later (3)	0/6 da same da (4)	+/4 da 3 da pr (0)	+ + same da	-2/1 da same da	-15.3/5 da (29.9)

Table 2. Meteorological Variables Associated with Major MLD 'peaks',
May through September, 1949 (2 pages)

Ocean Station NOVEMBER

Date	Synoptic Data 500 mb	 surface	Cloudiness (8ths)	Wind Force (Beaufort)	Sea (coded)	T_a-T_s (mean trend & max -C)	T_s (trend & ave max)	Pressure (mb)	ΔMLD (m)
9 Aug	T 3 da pr	sta front 4 da pr	-6/2 da 6 da pr (2)	-2/1 da same da (2)	0/5 da 3 da pr (2)	+/5 da 4 da pr (0)	+ + 'arrest' same da	-4/3 da 3 da pr	-29.3/7 da (11.9)
19 Aug	T 1 da later		-7/4 da same da (1)	-2/2 da 2 da pr (1)	0/3 da same da (2)	+/7 da 4 da pr (0)	+ + same da	-3/4 da same da	-13.4/5 da (5.5)
11 Sept	T same da		-7/2 da 2 da pr (1)	-2/1 da 1 da pr (0)	-2/1 da 1 da pr (1)	+/4 da 2 da later (0)2 da later	+ + same da	-3/1 da 1 da later	-5.5/2 da (10.1)
20 Sept	Low same da		-7/1 da 1 da pr (1)	-3/4 da 1 da later (1)	-2/3 da 2 da later (1)	+/3 da 1 da later (-1)	'arrest' from -2 to + 4 da	-4/7 da 1 da later	-4.3/1 da (13.7)

Table 2. Meteorological Variables Associated with Major MLD 'peaks', May through September, 1949 (cont'd)

Ocean Station ALFA

1. With passage of the predominant surface system, wind force decreased by two to five Beaufort, down to a range of Beaufort one to four. The decrease occurred over a period of one to five days, terminating zero to three days prior to the MLD 'peak'.

2. Total cloud cover decreased (in eighths) by one to eight, down to a range of zero to seven. The decrease occurred over a period of one to two days, terminating zero to five days prior to the MLD 'peak'. Five cases indicated no change of cloudiness from total sky coverage.

3. Air-sea surface temperature difference indicated a mean positive trend for two to nine days, terminating from three days prior to two days later than the MLD 'peak'. The maximum value reached ranged from zero to four degrees Centigrade, terminating from four days prior to one day later.

4. Coded sea-state decreased by two to five units, down to a range of one to six. The decrease occurred over a period of one to five days, terminating from three days prior to one day later than the MLD 'peak'.

5. The averaged sea-surface temperature curve indicated a positive trend, reached a maximum zero to four days later than the MLD 'peak', and conformed to the same general shape as the MLD trace.

6. The averaged MLD decreased 3.1 to 50.2 meters over a period of two to five days. The MLD 'peak' (minimum) ranged from 10.7 to 25.0 meters. Average MLD decrease for terminal sea conditions were as follows:

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Table 3. Summary of Meteorological Variables Associated with Major MLD 'peaks', May through September, 1949 (2 pages)

Sea state one to two: 17.8 meters

Sea state three to six: 4.8 meters.

7. A surface low, occlusion or frontal activity occurred in the area one to six days prior to the MLD 'peak', accompanied by a 500 mb low or trough within one day of the surface activity.

8. Surface pressure decreased from 4 to 28 mb over a period of one to six days, terminating one to six days prior to the MLD 'peak'.

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Table 3. Summary of Meteorological Variables Associated with Major MLD 'peaks', May through September 1949 (cont'd)

Ocean Station NOVEMBER

1. With passage of the predominant surface system, wind force decreased by zero to four Beaufort, down to a range of Beaufort zero to four. The decrease occurred over a period of one to five days, terminating zero to two days prior to the MLD 'peak'.

2. Total cloud cover decreased (in eighths) by one to seven, down to a range of one to seven. The decrease occurred over a period of one to six days, terminating zero to six days prior to the MLD 'peak'.

3. Air-sea surface temperature difference indicated a mean positive trend for two to nine days, terminating from four days prior to two days later than the MLD 'peak'. The maximum value reached ranged from minus two to plus two degrees Centigrade, four days prior to two days later.

4. Coded sea-state decreased by zero to six units, down to a range of one to four. The decrease occurred over a period of one to nine days, terminating from three days prior to three days later than the MLD 'peak'.

5. The averaged sea-surface temperature curve indicated a positive trend, reached a maximum zero to two days later than the MLD 'peak', and conformed to the same general shape as the MLD trace. In two cases, no clear minimum occurred, with no change of temperature from two days prior to four days later than the MLD 'peak'.

6. The averaged MLD decreased from 5.5 to 39.0 meters over a period of two to seven days. The MLD 'peak' (minimum) ranged from 3.7 to 34.2 meters. Averaged MLD decrease for terminal sea state one to four

Table 4. Summary of Meteorological Variables Associated with Major MLD 'peaks', May through September, 1949 (2 pages)

was 16.6 meters.

7. An identifiable surface trough or frontal system occurred in the area for only two cases, from three to four days prior to the MLD 'peak'. However, a clearly identified 500 mb trough or low could be associated with each MLD 'peak' (ranging from five days prior to two days later).

8. Surface pressure decreased from one to eight millibars over a period of one to seven days, terminating from three days prior to two days later than the MLD 'peak'.

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Table 4. Summary of Meteorological Variables Associated with Major MLD 'peaks', May through September, 1949 (cont'd)

Ocean Station PAPA

Date (ave & actual max)	Synoptic Data 500 mb	Synoptic Data surface	Cloudiness (8ths-mean)	Wind Force (Beaufort & mean-kts)	Sea (coded)	T_a-T_s (mean trend & max -C)	T_s (trend & ave max)	Pressure (mb)	ΔMLD (m) (ave & actual max)
17 May	Low 3 da pr	Low 4 da pr	-1/1 da 4 da pr (6)	0 chg/3 da 2 da pr (3)	0/3 da 2 da pr (2)1 da pr	+/6 da 1 da pr (+3)	+ + same da	-37/3 da 4 da pr	-50/6 da (12.4)
14 May				-23/7 da 1 da pr (8)					-75 3 da pr
1 June	T 2 da pr	Low 1-3 da pr	-1/1 da 4 da pr (7)	-2/2 da 3 da pr (2)	-2½/2 da 3 da pr (1)	+/3 da 2 da pr (+4)	+ + 1 da later	-20/5 da 1 da pr	-26/8 da (3.0)
29 May				-13/2 da 2 da pr (2)					-24 3 da pr
8 June	Low 4 da pr	Low 5 da pr	-4/1 da 3 da pr (4)	-3½/2 da 2 da pr (0)	-2/1 da 2 da pr (0)	+/4 da 2 da pr (+4)	+ + 1 da later	-14/2 da same da	-1.7/4 da (4.9)
6 Jun			(1) 2 da pr	-11/3 da 2 da pr (2)					-11 2 da pr
25 Jun	T 2-3 da pr	Low 5 da pr	-2/2 da 4 da pr (6)	-4½/3 da 2 da pr (1)	-3/3 da 2 da pr (0)	+/5 da 2 da pr (+6)	+ + 1 da later	-5/2 da 2 da pr	-15.1/5 da (5.5)
23 Jun			(4) 2 da pr	-21/3 da 2 da pr (5)					-30 2 da pr

Table 5. Meteorological Variables Associated with Major MLD 'peaks', May through August, 1958 (3 pages)

Ocean Station PAPA

Date (ave & actual max)	Synoptic Data 500 mb	Synoptic Data surface	Cloudiness (8ths-mean)	Wind Force (Beaufort & mean-kts)	Sea (coded)	T_a-T_s (mean trend & max -C)	T_s (trend & ave max)	Pressure (mb)	ΔMLD (m) (ave & actual max)
5 Jul	Low 0-3 da pr	Low 1-3 da pr	-1/1 da 2 da pr (7)	-2/1 da 3 da pr (0)	-1/1 da 3 da pr (0)	+/3 da 2 da pr (+3)	+ 'arrest' same da	-9/2 da 3 da pr	-17.3/4 da (7.6)
3 Jul			(6) same da	-6/1 da 3 da pr (3)					-25 2 da pr
14 Jul	T 3 da pr	Occ 2 da pr	-1/1 da 1 da pr (7)		-1/2 da same da (2)	+/3 da same da (+4)	+ + 2 da later	-6/2 da 3 da pr	-3.6/4 da (7.0)
14 Jul				-13/2 da same da (8)					-15 same da
25 Jul	T 2 da pr	CF 2 da pr	-1/1 da 2 da pr (7)	-4/1 da 2 da pr (0)	-1/1 da 1 da pr (2)	+/2 da same da (+3)	+ 1 da later	-12/2 da same da	-3.0/2 da (20.1)
24 Jul				-11/2 da 2 da pr (8)					-24 1 da pr
14 Aug	Low 1-2 da 2 da pr	Low 1-3 da 2 da pr	-1/1 da 3 da pr (7)	-4/3 da 2 da pr (1)	-2/2 da 2 da pr (2)	+/2 da 2 da pr (+4)	+ same da	-16/4 da 1 da pr	-5.3/5 da (29.9)
12 Aug			(5)2 da pr	-16/2 da 2 da pr (11)					-35 2 da pr

Table 5. Meteorological Variables Associated with Major MLD 'peaks', May through August, 1958 (cont'd)

Ocean Station PAPA

Date (ave & actual max)	Synoptic 500 mb	Data surface	Cloudiness (8ths-mean)	Wind Force (Beaufort & mean-kts)	Sea (coded)	T_a-T_s (mean trend & max -C)	T_s (trend & ave max)	Pressure (mb)	ΔMLD (m) (ave & actual max)
31 Aug	T same da	Low 1 da pr	-1/1 da 1 da pr (7)	-4½/3 da same da (1½)	-4/3 da same da (1)	-/5 da same da (-2)	no 'peak'	-2/1 da same da	-3.6/1 da (28.4)
31 Aug			(6) same da	-15/3 da (1) 1 da later					-39 same da

Table 5. Meteorological Variables Associated with Major MLD 'peaks', May through August, 1958 (cont'd)

Ocean Station PAPA

1. With passage of the predomina . surface system, 24 hour mean wind force decreased by 6 to 23 kts, down to a range of 1 to 11 kts. The decrease occurred ove a period of one to seven days, terminating from three days prior to one day later than the MLD 'peak'.

2. Total cloud cover decreased (in eighths) by one to four down to a . age of four to seven. The decrease occurred over a period of one to two days terminating one to four days prior to the MLD 'peak'. In six cases, cloudiness continued to decrease to a value of one to six terminating zero to two days prior to the MLD 'peak'.

3. Air-sea surface temperature difference indicated a mean positive trend for two to six days, terminating zero to two days prior to the MLD 'peak'. The maximum value reached ranged from a plus two to plus six degrees Centigrade, zero to three days prior.

4. Coded sea-state decreased by zero to four units, down to a range of zero to two. The decrease occurred over a period of one to three days, terminating from zero to three days prior to the MLD 'peak'.

5. The averaged sea-surface temperature curve indicated a positive trend, reached a maximum zero to two days later than the MLD 'peak', and conformed to the same general shape as the MLD trace. In two cases, no clear minimum occurred.

6. The averaged MLD decreased from 3.0 to 50.0 meters over a period of one to eight days. The MLD 'peak' (minimum) ranged from 3.0 to 29.9 meters. Average smoothed MLD decrease with a terminal sea-state

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Table 6. Summary of Meteorological Variables Associated with Major MLD 'peaks', May through August, 1958 (2 pages)

of one to three was 11.9 meters. Average actual maximum MLD decrease relative to the MLD 'peak' was 28.9 meters occurring zero to three days prior, with a range from 11 to 75 meters.

7. An identifiable surface low, occlusion or frontal system occurred in the area for each case, from one to five days prior to the MLD 'peak'. A 500 mb low or trough could be associated with each surface system (occurring within one day).

8. Surface pressure decreased 5 to 37 mb over a period of one to five days, terminating from zero to four days prior to the MLD 'peak'.

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Table 6. Summary of Meteorological Variables Associated with Major MLD 'peaks', May through September, 1958 (cont'd)

	Individual Data					Paired Data			
Units	$\overline{T}_{02}$	$\overline{T}_{17}$	$\Delta\overline{T}_{02-17}$	$\overline{T}_{02,17}$	$\overline{T}_{24}$	$\overline{T}_{02}$	$\overline{T}_{17}$	$\Delta\overline{T}_{02-17}$	$\overline{T}_{24}$
C	10.79	10.56	-0.23	10.68	10.68	10.79	10.54	-0.25	10.67
	$\overline{MLD}_{02}$	$\overline{MLD}_{17}$	$\Delta\overline{MLD}_{02-17}$	$\overline{MLD}_{02,17}$	$\overline{MLD}_{24}$	$\overline{MLD}_{02}$	$\overline{MLD}_{17}$	$\Delta\overline{MLD}_{02-17}$	$\overline{MLD}_{24}$
m	9.93	14.03	+4.10	11.98	12.26	9.93	14.40	+4.47	12.17

Table 7. Mean Bathythermograph Data, Ocean Station PAPA, June, 1958

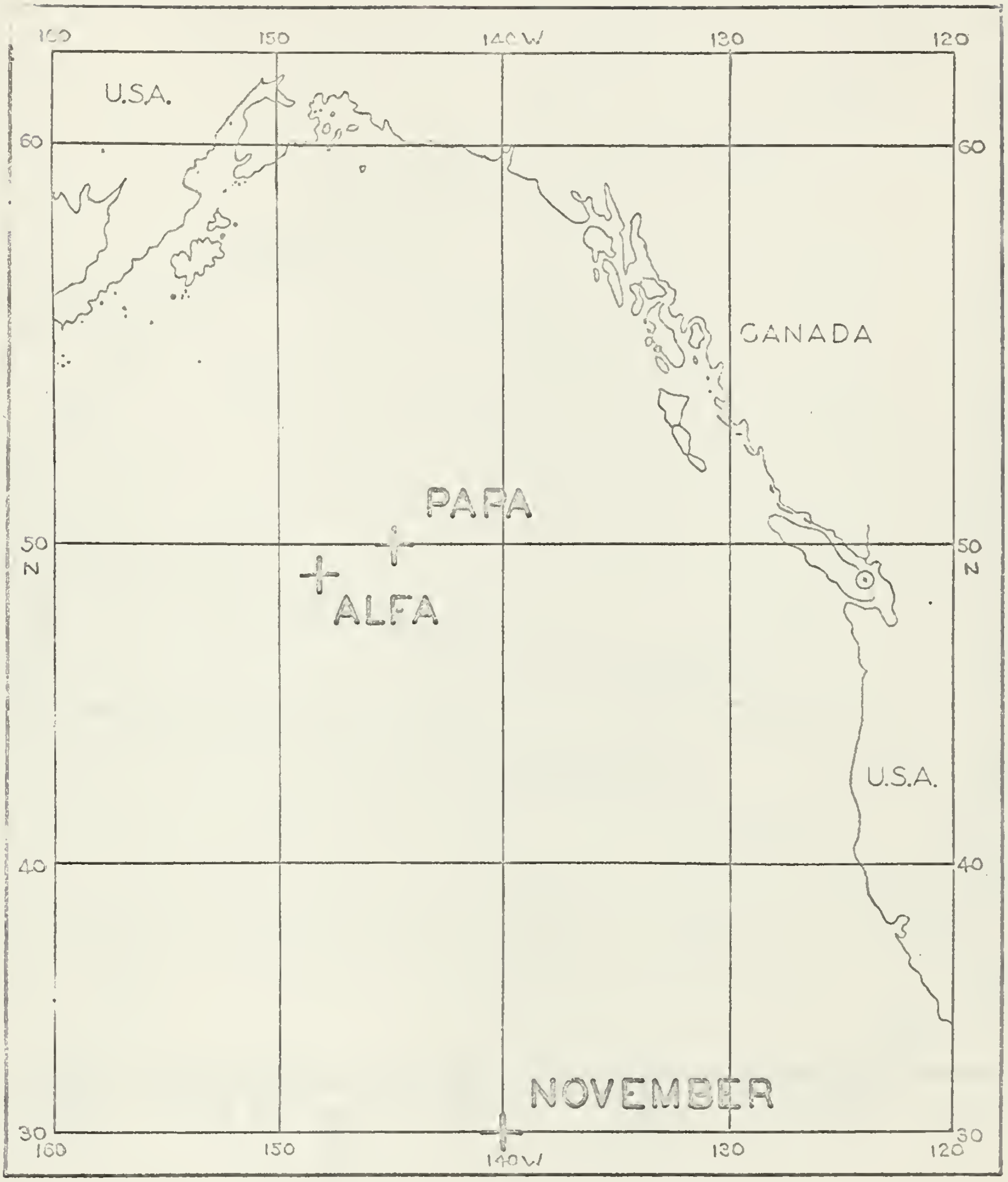

Figure 1. Chart of Northeast Pacific Ocean showing Ocean Stations ALFA (49N - 148W), NOVEMBER (30N - 140W), and PAPA (50N - 145W)

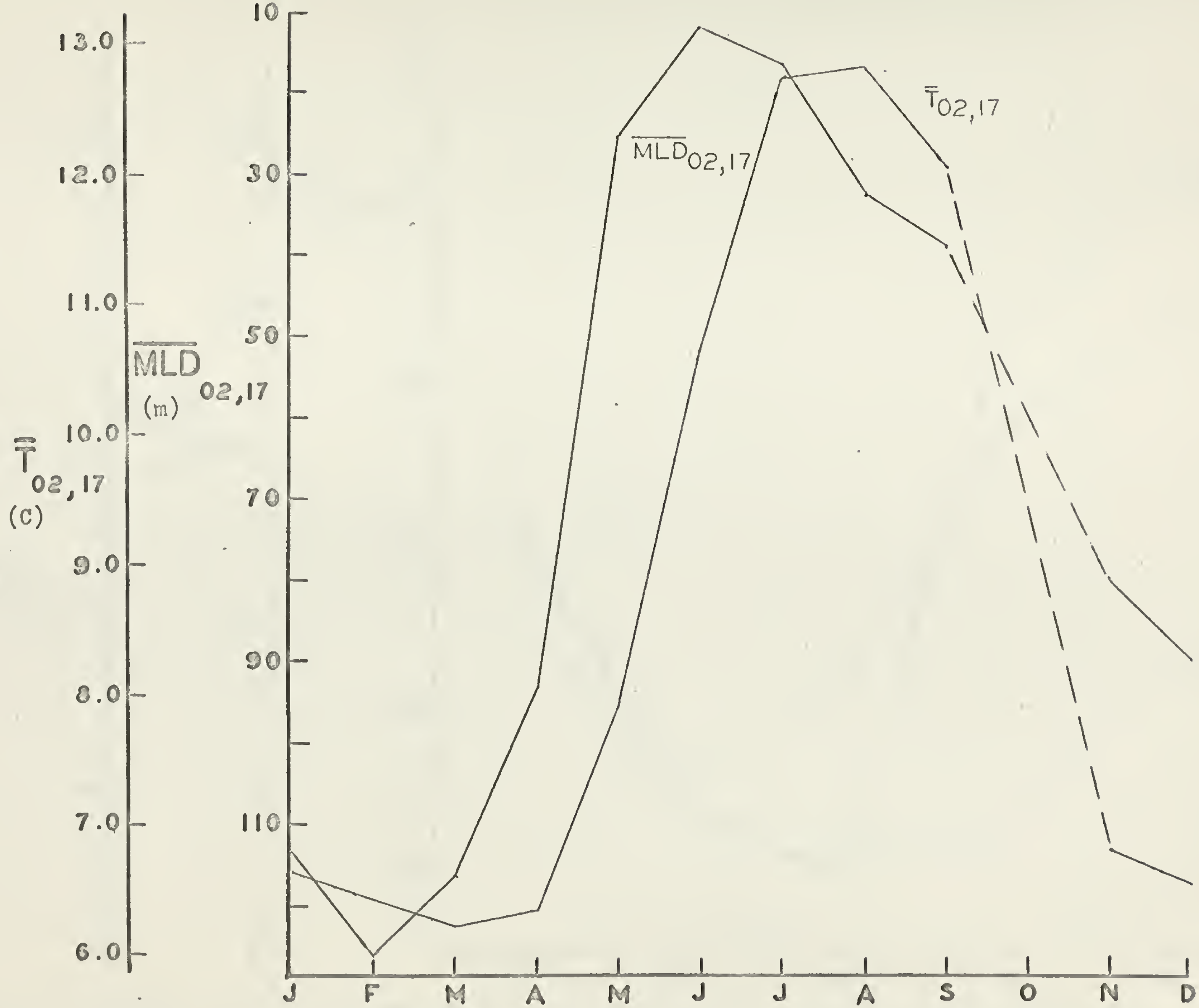

Figure 2. Monthly Mean Bathythermograph Data, Ocean Station PAPA, 1958

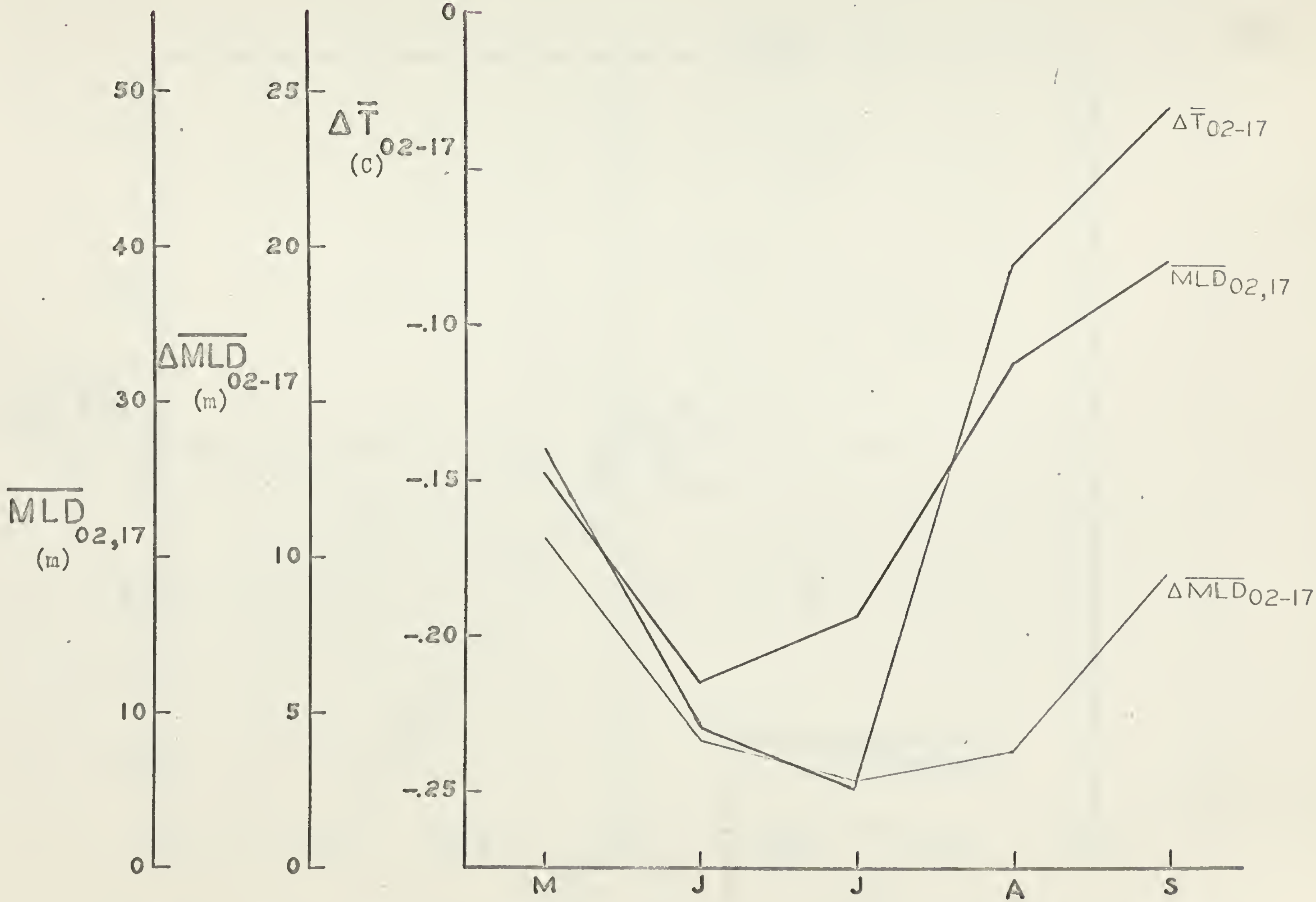

Figure 3. Monthly Mean Bathythermograph Data, Ocean Station PAPA, May through September, 1958

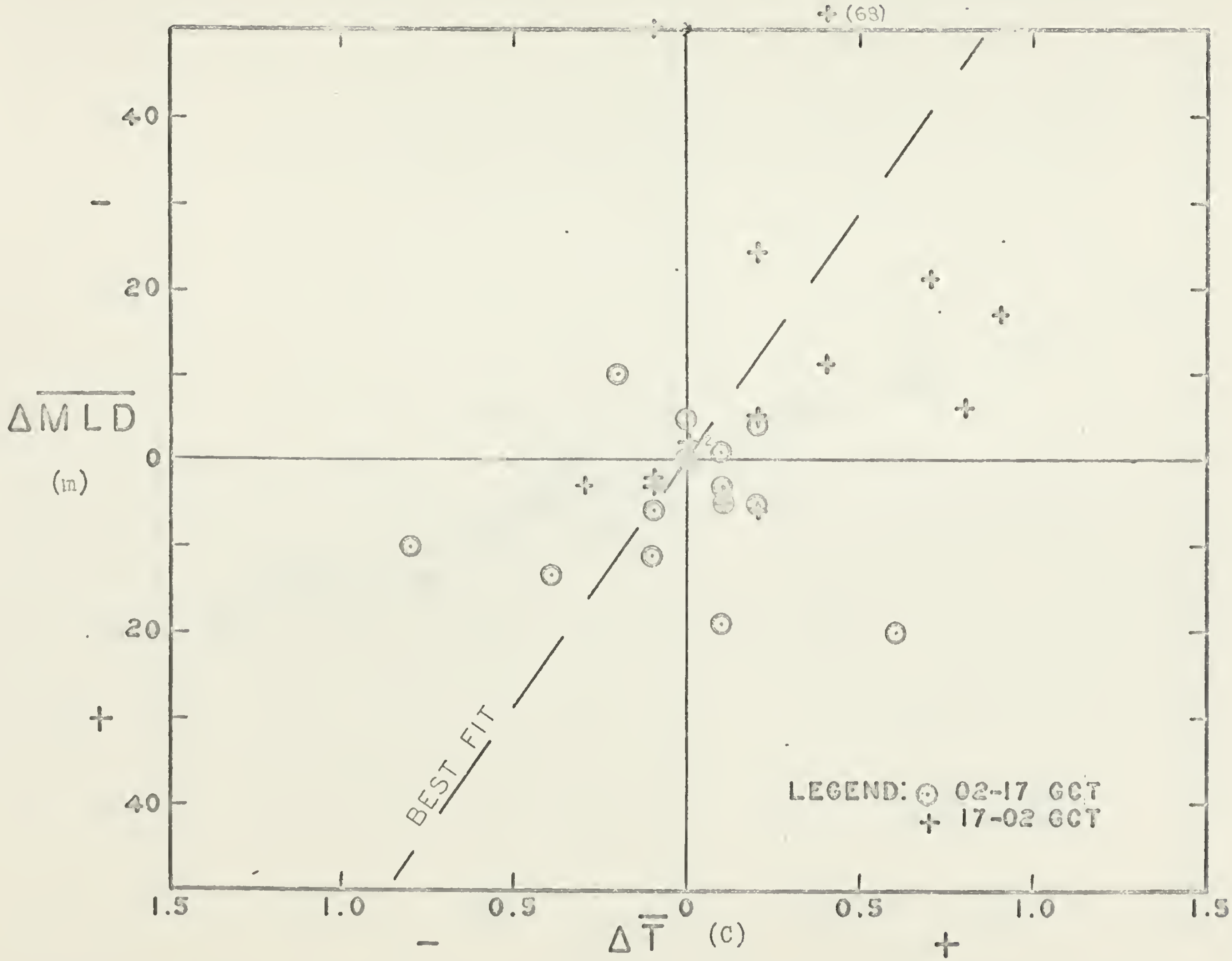

Figure 4. Diurnal Bathythermograph Data, Ocean Station PAPA, May, 1958

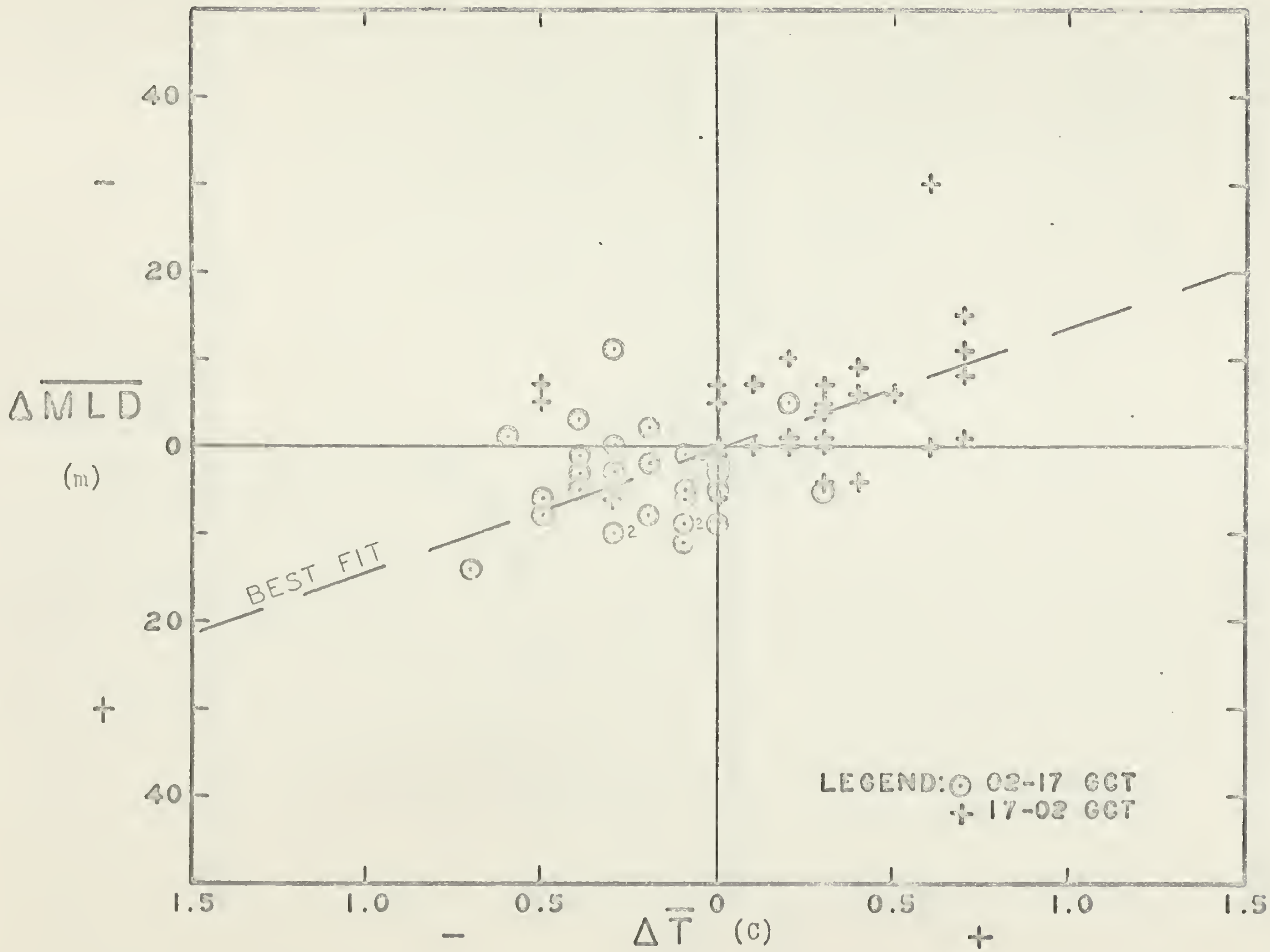

Figure 5. Diurnal Bathythermograph Data, Ocean Station PAPA, June, 1958

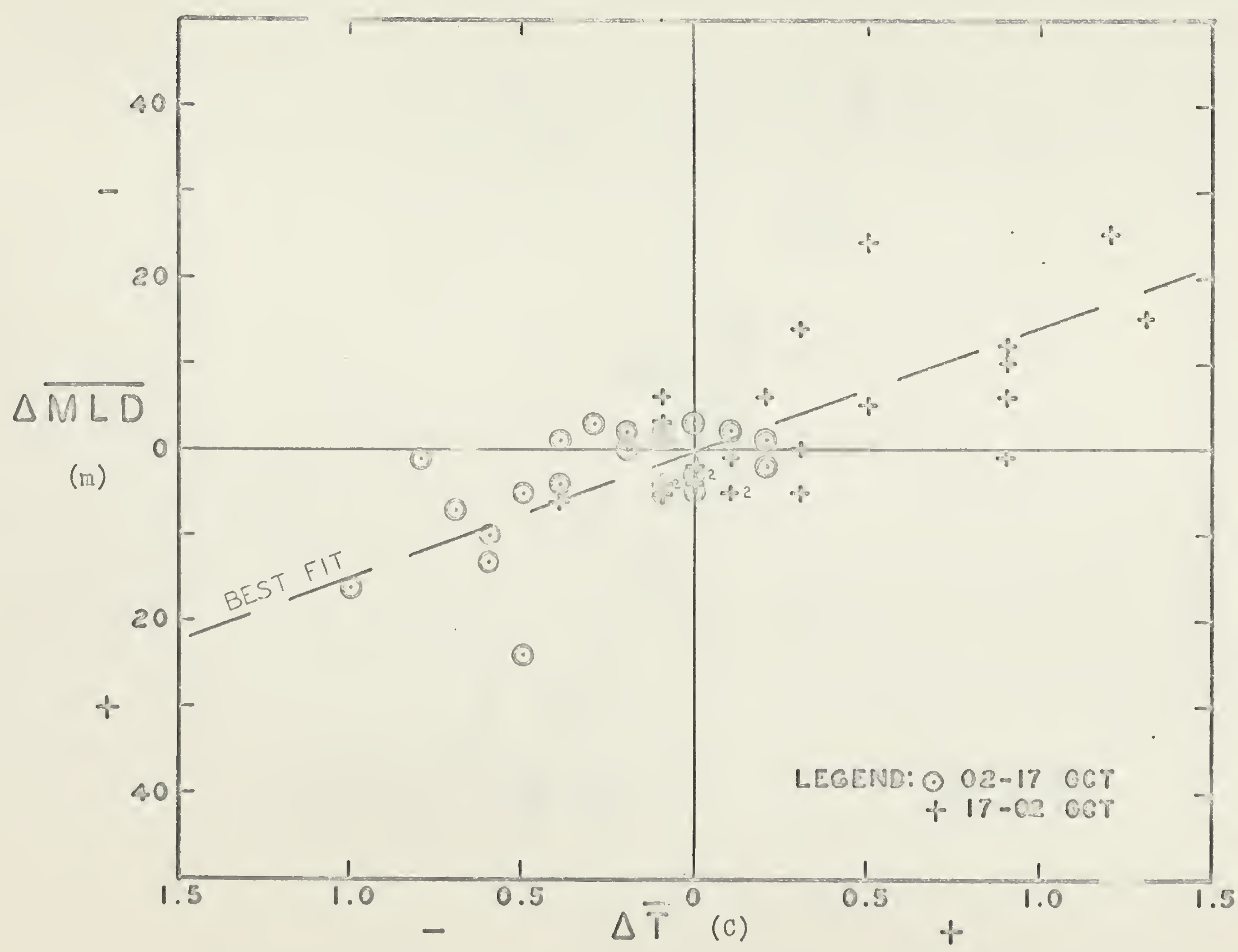

Figure 6. Diurnal Bathythermograph Data, Ocean Station PAPA, July, 1958

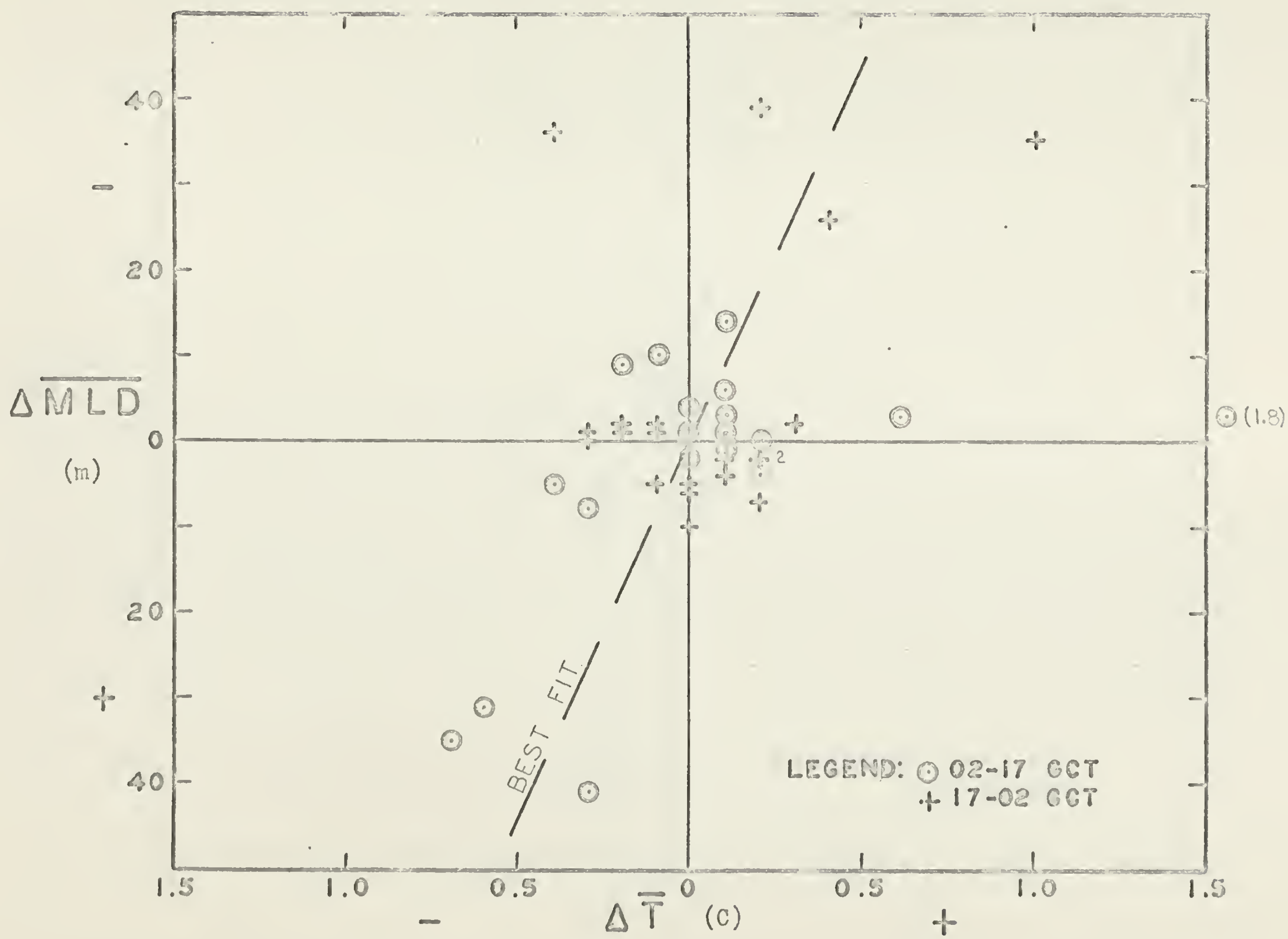

Figure 7. Diurnal Bathythermograph Data, Ocean Station PAPA, August, 1958

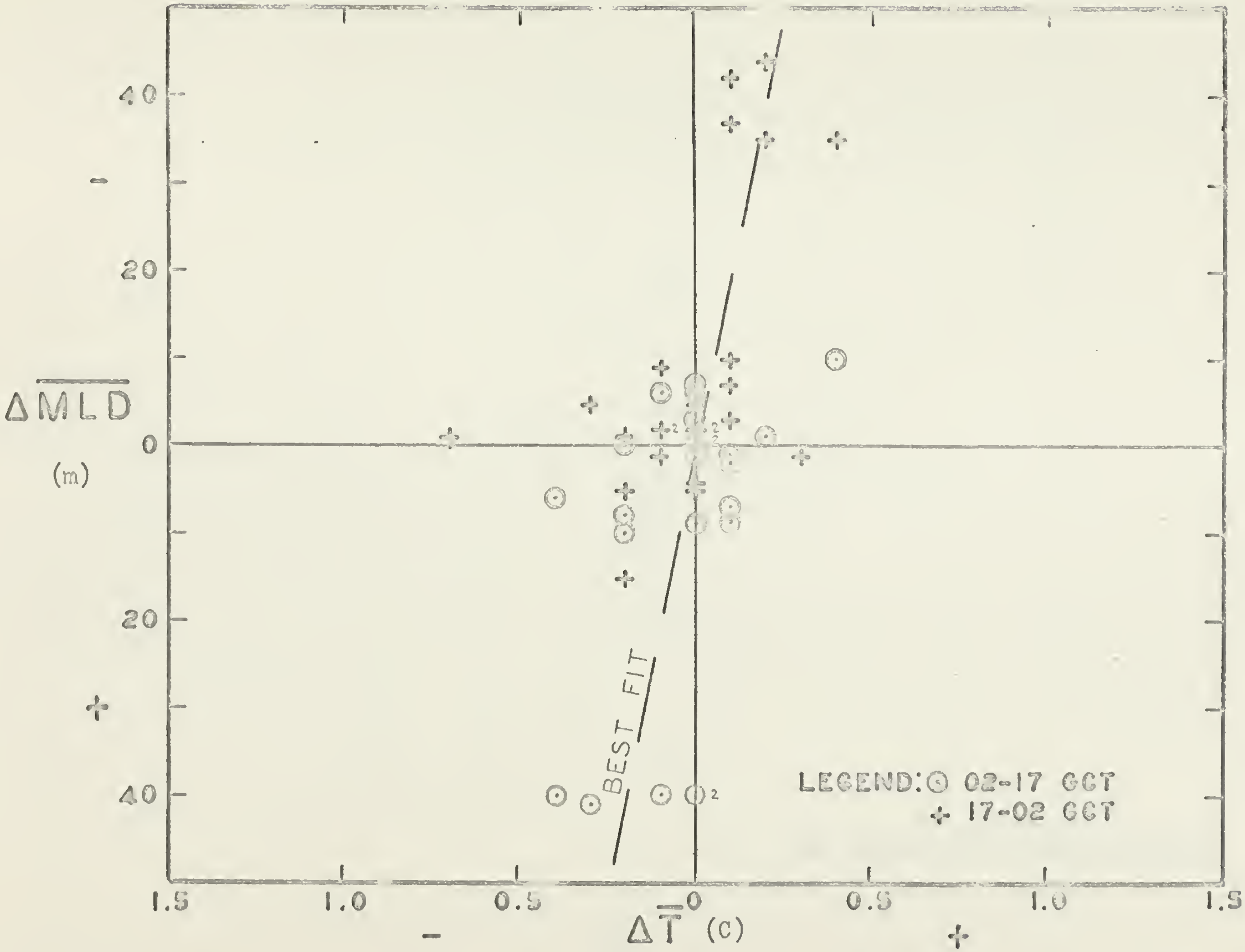

Figure 8. Diurnal Bathythermograph Data, Ocean Station PAPA, September, 1958

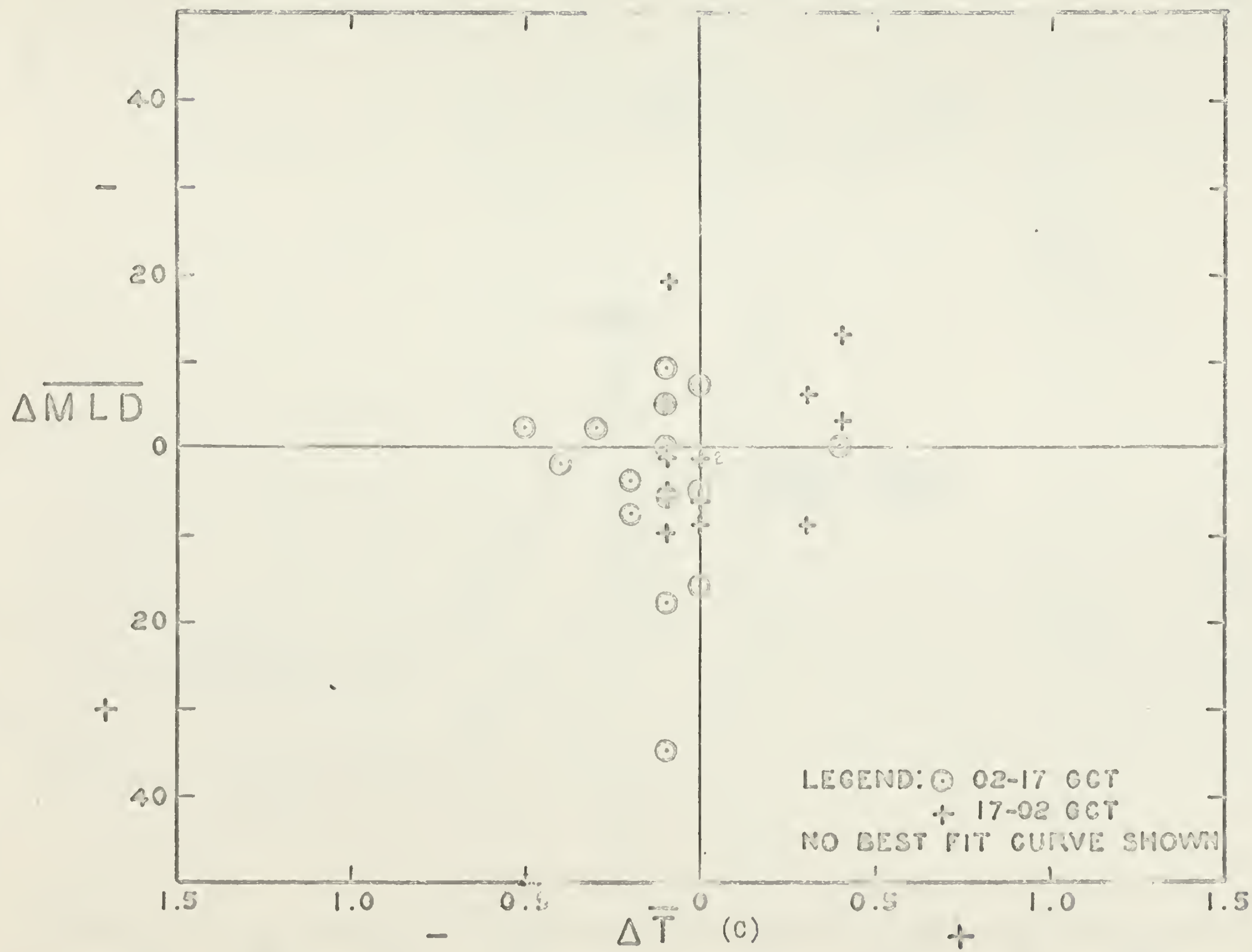

Figure 9. Diurnal Bathythermograph Data, Ocean Station PAPA, November, 1958

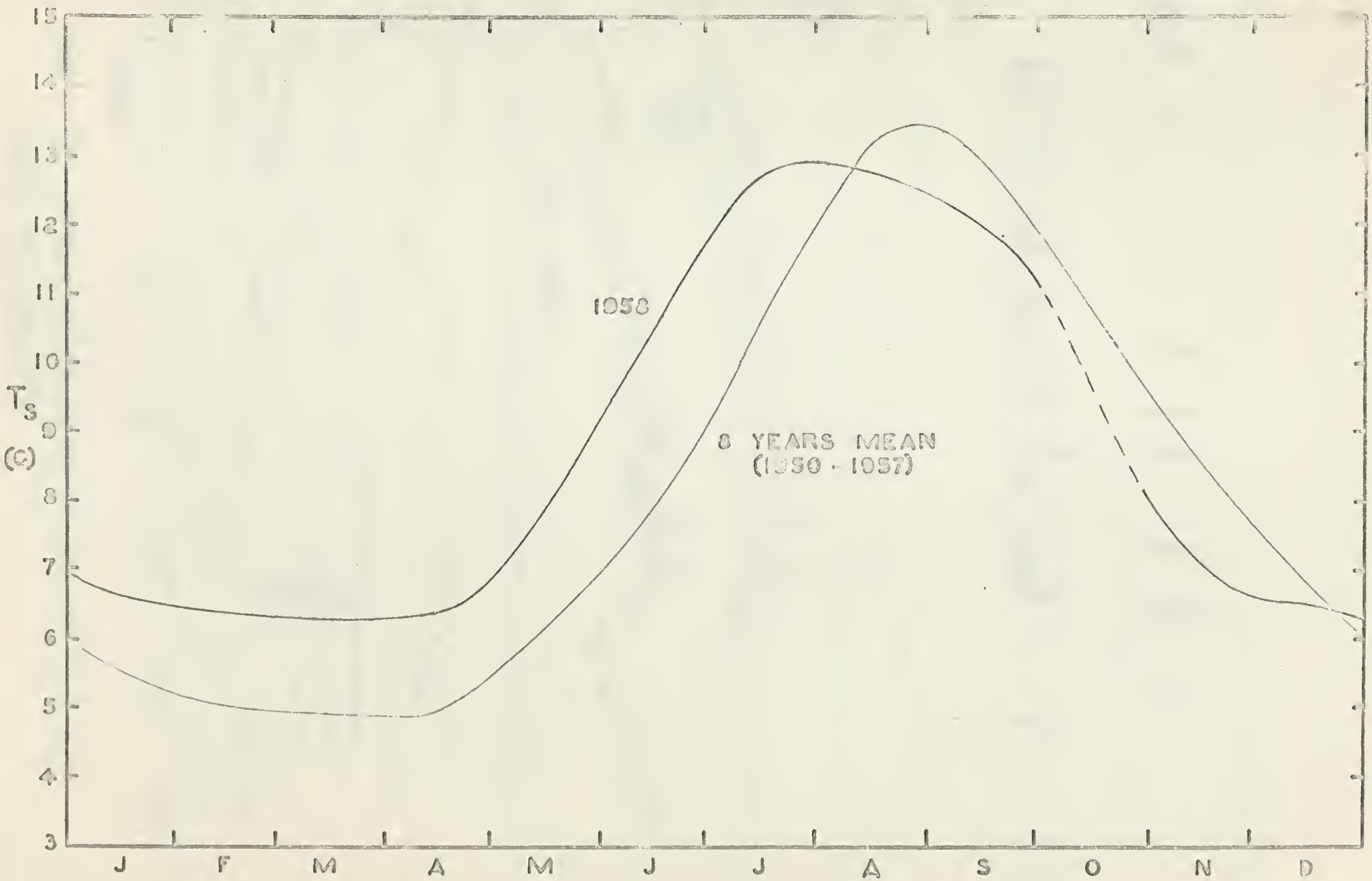

Figure 10. Monthly Mean Sea-surface Temperature, Ocean Station PAPA, 1958 and 1950 - 1957 Mean [13]

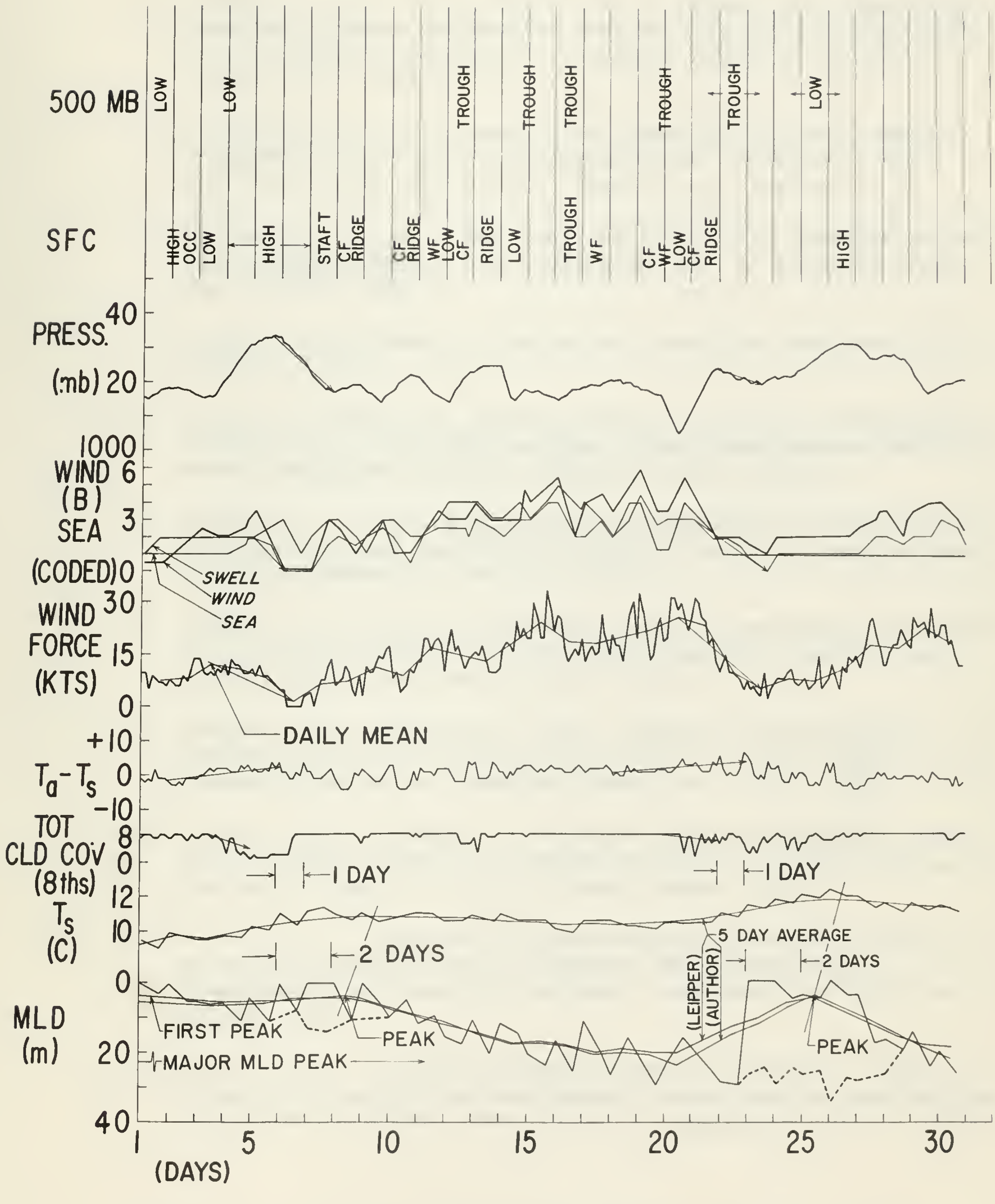

Table I. Time-Series of Meteorological Variables and MLD, Ocean Station PAPA, June, 1958

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